PERFORMANCE OF THE BEPC AND PROGRESS OF THE BEPCII

C. Zhang for BEPC & BEPCII Teams
Institute of High Energy Physics, CAS, P.O. Box 918, Beijing 100039, China

Abstract

The performance of the Beijing Electron-Positron Collider (BEPC) and plans of its second phase construction, i.e. the BEPCII, are reported. The BEPC has been well operated for 15 years with many exciting high energy physics and synchrotron radiation research results since it was put into operation in 1989. As the natural extension of the BEPC, the BEPCII project has started its construction since the beginning of 2004. The design luminosity of the BEPCII is $1\times10^{33}cm^{-2}s^{-1}$ at 1.89 GeV with a double-ring structure. The performance of the BEPCII as a synchrotron radiation source will also be improved with the expected beam current of 250mA at 2.5 GeV. Some key technologies are being developed in order to achieve the goal of the project.

PERFORMANCE OF THE BEPC

The BEPC was constructed for both high energy physics (HEP) and synchrotron radiation (SR) researches [1]. The BEPC-accelerators consist of a 202 m long electron-positron linac injector, a storage ring with circumference of 240.4 m and, in connection with each other, 210 m transport lines. There are two interaction points in the storage ring. A general-purpose detector, the Beijing Spectrometer (BES), is installed in the south interaction region (IR). The Beijing Synchrotron Radiation Facility (BSRF), equipped with 4 insertion devices and 12 beamlines, is flanking the east and west of the southern areas of the storage ring. Figure 1 illustrates the layout of the BEPC.

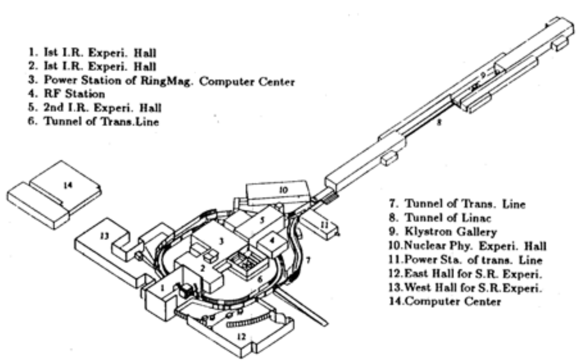

Figure 1: Layout of the BEPC.

As a unique e^+-e^- collider operating in the τ and charm region and a first synchrotron radiation source in China, the machine has been well operated for 15 years. Table 1 lists its main parameters.

Table 1: Main parameters of the BEPC

Operation energy (E)	GeV	1.0-2.5
Injection energy (E_{inj})	GeV	1.3
Circumference (C)	m	240.4
β at IP (β^*_x/β^*_y)	cm	120/5
Tunes ($\nu_x/\nu_y/\nu_z$)		5.8/6.7/0.02 (HEP) 8.72/4.75/0.02 (SR)
Emittance (ε_{x0})	mm·mr	0.4 @1.55 GeV (HEP) 0.08@2.2GeV(SR)
RF frequency (f_{rf})	MHz	199.53
Bunch number (N_b)		1×1(HEP), 60-80 (SR)
Beam current (I_b)	mA	22 @1.55 GeV (HEP) 140@2.2GeV (SR)
Beam-beam param. ξ_y		0.04
Beam lifetime τ	hrs.	8-10 (HEP), 20-30 (SR)
Luminosity	$cm^{-2}s^{-1}$	5×10^{30}@1.55 GeV 1.2×10^{31} @1.89 GeV

As a result of the successful operation, the BEPC/BES accurately measured the mass of τ lepton; carried out R-scan in the center-of-mass energy region of 2–5 GeV; collected a largest data sample of J/ψ and ψ' events in the world. Recently, a narrow peak was observed near the 2 times of the proton energy in the $M(p\bar{p})$ distribution for $J/\psi\to\gamma\ p\bar{p}$ decays using the BES-II 58 million J/ψ events [2], shown in Figure 2. This is a significant result, although it is still too early to determine if it is a proton-antiproton bond state or multiple quark state.

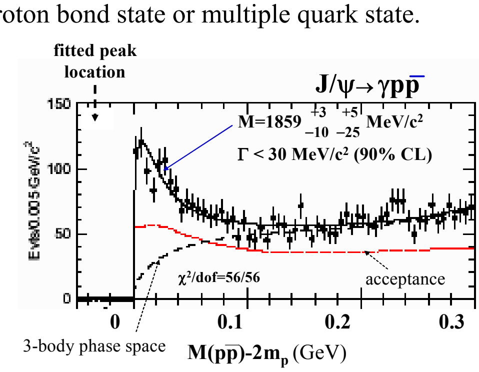

Figure 2: The new peak observed near 2M(pp).

The physics opportunity in the charm-τ region calls higher luminosity. The BEPCII, with a luminosity goal of two orders of magnitude higher than the present BEPC, is its natural extension.

BASIC DESIGN OF THE BEPCII

The BEPCII will be operated in the beam energy region of 1.0-2.1 GeV so that its physical potential in τ and charm range is preserved. As the physics is concentrated at the J/ψ (3097), ψ(3686), ψ(3770) and nearby, the collider is optimized at the beam energy of 1.89 GeV. The detail can be found in its design report [3]

Luminosity from BEPC to BEPCII

As a measure of the event production rate, luminosity is one of the most important parameters in colliders. The luminosity of an e^+-e^- collider is expressed as

$$L(\mathrm{cm}^{-2}\mathrm{s}^{-1}) = 2.17\times10^{34}(1+r)\xi_y \frac{E(GeV)k_b I_b(\mathrm{A})}{\beta_y^*(\mathrm{cm})}, \quad (1)$$

where $r=\sigma_y^*/\sigma_x^*$ is the beam aspect ratio at the interaction point (IP), ξ_y the vertical beam-beam parameter, β_y^* the vertical envelope function at IP, k_b the bunch number in each beam and I_b the bunch current.

With the parameters of the BEPC, E = 1.55 GeV, ξ_y = 0.04, β_y^* = 5cm, k_b = 1 and I_b = 22 mA, and assuming $r = \sigma_y^*/\sigma_x^* \approx \beta_y^*/\beta_x^*$ = 0.042, the luminosity of the BEPC is calculated from eq. (1) as $0.62\times10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which agrees well with the measured value of $0.5\times10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 1.55 GeV. Table 2 describes the strategy of the luminosity upgrading from the BEPC to the BEPCII.

Table 2: Luminosity strategy from BEPC to BEPCII

Parameters	BEPC	BEPCII
Beta function at IP β_y^* (cm)	5.0	1.5
Bunch number k_b	1	93
Beam-beam parameter ξ_y	0.04	0.04
Current per bunch I_b (mA)	35	9.8
Luminosity gain L_{BEPCII}/L_{BEPC}	1	96

In order to obtain a high duty factor of the collision, the injection time should be shorter than half an hour. The injector of the BEPCII should be capable of the full-energy top-off injection up to 1.89 GeV, and the positron injection rate should be higher than 50 mA/min. As the machine will also be operated as an SR source, the upgrade of the collider should also provide an improved SR operation performance with higher beam energy and higher intensity. The SR beam ports should be reserved for BSRF and more beam lines will be equipped in the quadrant I of the storage ring tunnel, where electron beams are stored in the outer ring.

Main Parameters

Based on the strategy of the luminosity upgrading of the BEPC, the design for the BEPCII is worked out. Table 3 summarizes the main parameters of the BEPCII.

Table 3: Main parameters of the BEPCII

Optimised Beam Energy E		GeV	1.89
Circumference C		m	237.53
Bunch Number k_b			93
Bunch Current I_b		mA	9.8
Beam Currents I_{beam}	Colliding	mA	910
	SR		250 (2.5GeV)
RF Frequency f_{RF}		MHz	499.8
RF Voltage per ring V_{RF}		MV	1.5
Beta Function at IP β_x^*/β_y^*		cm	100/1.5
Emittance $\varepsilon_x/\varepsilon_y$		nm·rad	144/2.2
Bunch Length σ_{z0}/σ_z		cm	1.3/1.5
Energy spread σ_e			5.16×10^{-4}
Bunch Spacing S_b		m	2.4
Impedance $\|Z/n\|_0$		Ω	< 0.7
Tune $\nu_x/\nu_y/\nu_z$			6.53/7.58/0.034
Damping Time $\tau_x/\tau_y/\tau_z$		ms	25/25/12.5
Beam-beam Parameter ξ_x/ξ_y			0.04/0.04
Crossing Angle ϕ_c		mrad	11×2
Luminosity L		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1×10^{33}

The Double-ring Structure

A substantially higher performance could be reached with the double-ring option for much more bunches are allowed to be in collision, as seen in Table 3. Figure 3 shows the layout of the double ring arrangement in the BEPC tunnel.

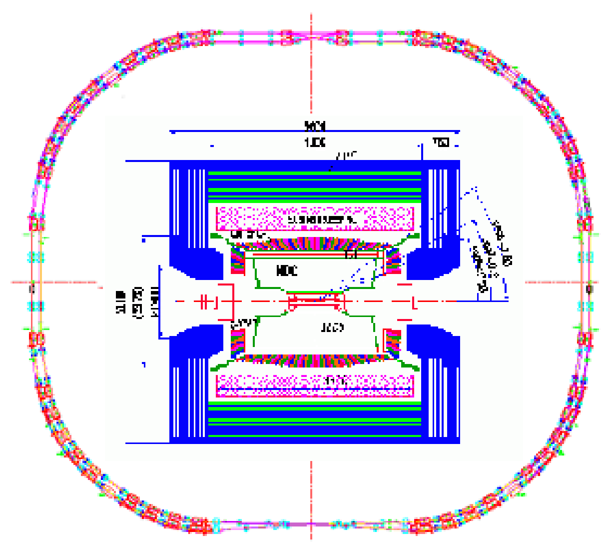

Figure 3: The layout of the double ring of the BEPCII.

The inner ring and the outer ring cross in the northern and southern IP's. A bypass connects the outer ring in the northern IR and a pair of bending coils in superconducting magnets serves this purpose in the southern IR so that electron beams can circulate in the outer ring for the dedicated synchrotron radiation operation of the BEPCII. The design beam currents for SR operation are 250 mA at 2.5 GeV.

Impedance and Collective Effects

Control of the bunch length and impedance is one of the crucial issues for the success of the micro-β scheme in the BEPCII. There are experimental and theoretical evidences showing that bunch length in a collider should be smaller or comparable to the β-function at IP. The bunch length in the BEPC is about 5 cm in the operation condition of I_b~20 mA, V_{rf}~0.6 MV at 1.55 GeV. In order to operate the collider with micro-β scheme of $\beta_y^* = 1.5$ cm, the bunch length σ_l in the BEPCII should be less than 1.5 cm. With the 500 MHz superconducting cavities of $V_{rf} = 1.5$ MV, the natural bunch length $\sigma_{l0} = 1.1$ cm. However, the finite impedance due to the discontinuity of the vacuum pipes in the storage ring will make the bunch lengthening against its intensity. The bunch length will be increased due to potential well distortion and microwave instability. The threshold of microwave instability is

$$I_{th} = \frac{\sqrt{2\pi}\alpha_p \frac{E}{e} \sigma_{e0}{}^2 \sigma_{l0}}{R \left| \frac{Z}{n} \right|_{eff}}, \qquad (2)$$

where α_p is the momentum compaction factor, E the energy of the beam, σ_{e0} and σ_{l0} the natural rms energy spread and natural rms bunch length respectively, R the mean radius of the ring, $|Z/n|_{eff}$ the longitudinal effective coupling impedance. It predicts the instability threshold of 0.97Ω for the design bunch current of 9.8 mA.

In order to make the impedance $|Z/n|_{eff}$ smaller than 0.97 Ω, all the vacuum components such as bellows, kickers, separators, BPM's, masks, connectors, valves, pumps, and SR beam ports must be carefully designed. The computer code of MAFIA is applied to compute the impedance of vacuum components in comparison with measurements. According to the impedance budget, the total inductance of BEPCII is about 28.9 nH, corresponding to $|Z/n|_0$~0.23Ω. The design study shows that it is possible to control the impedance under the threshold impedance of the microwave instability if the vacuum chamber is rebuilt by adopting the state of art technology in the BEPCII. The computation of the wakefield of the storage rings and simulation for bunch lengthening are worked out for the BEPCII.

The coupled bunch instabilities due to the beam-cavity interaction is estimated based on the high order mode (HOM) data of the superconducting cavities. The growth rate of the dangerous modes of the coupled bunch instability with N_b= 99, I_b = 9.8 mA are τ_{rise} = 12.8 ms (longitudinal m = 0) and τ_{rise} = 26.6 ms (transverse m = 1), which close to the SR damping time of the BEPCII at 1.89 GeV of $\tau_x/\tau_y/\tau_z$ = 25/25/12.5 ms.

The real part of the impedance may cause the resistive wall instability. The major part of the vacuum chamber of the BEPCII is made of aluminium. The computation with the code of ZAP indicates that the most dangerous mode of the resistive wall instability in the BEPCII has the growth time of 1.6 ms for ν_y=7.9 with N_b = 99, I_b = 9.8 mA at the present design tunes. The estimation is done with the 99 uniformly distributed bunches in the ring which is considered as the up limit of the instability for 93 bunches with a small gap in the BEPCII. The instabilities can be handled with a feedback system.

The electron and positron beams will circulate in the separated rings in the BEPCII, so the foreign particle caused instabilities such as ion trapping, fast ion instability, dust effect and electron cloud instability, are concerned. The theoretical and experimental studies on these instabilities in the BEPC are in progress[4].

The head-on beam-beam parameter of 0.04 is demonstrated in the BEPC. A finite-crossing angle of ±11 mrad is adopted for the IP of the BEPCII. With this crossing angle, the strong parasitic beam-beam interactions can be avoided for the 2.4 m bunch spacing. The electron and positron bunches are further than $10\sigma_x$ separated at the parasitic collision points, which seem large enough. However, the sophisticated beam-beam simulation with a crossing angle needs to be carried out in further detail.

The beam lifetime determines the duty factor of the storage ring operation. Many coherent and incoherent effects will influence on the beam lifetime. In the BEPCII, the major effects are considered as beam-gas interaction, beam-beam bremsstrahlung, Touschek effect and quantum effect. The overall beam lifetime is estimated as about 2.7 hours, and then the optimized collision time is calculated as 1.0 hours with the maximum average luminosity $\langle L \rangle_{max}$=(0.5~0.6)×10^{33} $cm^{-2}s^{-1}$.

KEY TECHLOLOGIES & SYSTEMS

Number of key technologies and hardware subsystems need to be developed for the BEPCII, including injector upgrading, superconducting RF system, low impedance kickers, vacuum system, superconducting insertion magnets and IR and some others.

Injector Upgrading

The BEPC injector is a 202meter electron linac with 16 RF power sources and 56 S-band RF structures. The positron production system is located at down stream of second RF power source.

The BEPCII requires the injector in two aspects. One is the full energy injection to the storage rings, i.e. $E_{inj} \geq$ 1.89 GeV, the other is that the positron intensity satisfies the required injection rate of 50 mA/min. In order to realize the full energy top-off injection up to 1.89 GeV, the present-used 34 MW klystrons shall be replaced with the new 45-50 MW devices. The present modulators will be upgraded with new pulse transformer oil tank assembly, PFN, thyratron, charging choke and DC power supplies.

The technical measures taken for increase of positron intensity in the BEPCII injector are listed in Table 4. The new positron source is shown in Figure 4

Table 4: Technical measures for increasing e^+ intensity

Technical measure	Gain
To increase e^- beam current on e^+ target I_G=2.5A↗ 6A	2.4
To increase the repetition rate f_r=12.5Hz ↗ 50Hz	4
To enhance bombarding energy for e^+ E_c = 140MeV↗240MeV	1.7
New positron source of higher yield η =1.4%↗ 2.7% ($e^+/e^-\cdot$GeV)	1.9
Two bunches injection n_b =1↗ 2	1.6
Reduction of pulse length T = 2.5ns↘1ns	0.4
Total intensity enhancement factor	19.8

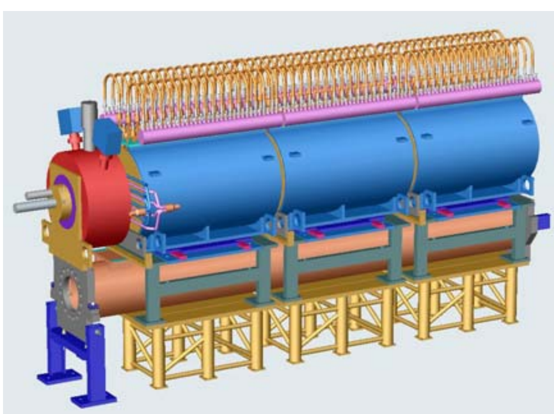

Figure 4: The positron production system.

500 MHz Supercunducting RF System

The BEPC has been operating with 200 MHz normal conducting cavities. As mentioned in the previous sections, in order to meet the design goal of higher luminosity with shorter bunch length, one needs to increase RF frequency and enhance accelerating voltage.

Normal conducting and superconducting RF cavities are compared for the BEPCII. The superconducting scheme is chosen for its larger accelerating gradient, smooth structure and large beam port, transmitted-out of HOMs and low RF power consuming. Two superconducting cavities will be used in the BEPCII providing 2×1.5 MV RF voltage. The cavities will be powered with two 250 kW RF transmitters.

The refrigeration capability of 300W is required for two supercunducting cavities. Two 500W refrigerators will be applied in the BEPCII. One is for the cavities and another is for the micro-β insertion supercunducting magnets and the detector solenoid.

Injection Kickers

The study has shown that the kickers in BEPC are one of major sources of the coupling impedance in BEPC, where single turn air coils are located inside vacuum chambers of the kickers.

Two schemes were considered for the BEPCII kickers. One is ferrite magnet outside the vacuum with ceramic beam pipe; another is the slotted-pipe magnet inside the vacuum tank. We choose a modified slotted pipe kicker design with the coating strips on ceramic bar instead of metallic plates as the beam image current return paths. With this design, the balance between the field uniformity and the beam impedance is advantaged.

Magnets and Power Supplies

The double-ring structure of BEPCII requires doubling the number of magnets. There are all together 357 magnets of different types, including 44 old and 48 new bends, 28 old and 89 new quads, 72 sextuples, 22 old and 54 new correctors. The optimised energy is 1.89GeV, while the magnets can operate normally at 2.1GeV. Due to space limitation of the BEPC existing tunnel, the size of inner ring magnets should be as small as possible. The magnets are designed giving room for the antechamber on horizontal plane. The cooling water pressure drop on all designed magnets is kept below 6 kg/cm^2, same as it is in the BEPC. There are 40 girders in the arcs of each ring, where the magnets and other components are mounted. The layout of the installation is shown in the Figure 5.

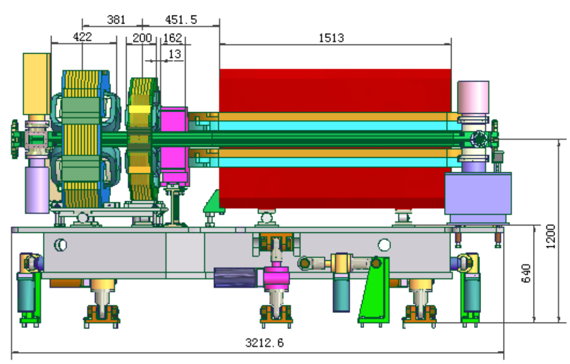

Figure 5: The magnets mounted on a girder.

More magnets in two rings need more power supplies, while the flexibility of the lattice design needs another factor of two power supplies. The total number of power supplies increases from 90 of the present BEPC to 326 of BEPCII storage rings, where 4 power supplies are used for bends, 122 for quads, 36 for sextupoles, 14 for the special IR magnets, 14 for IR superconducting magnets, 2 for injection ion septa and 134 for correctors.

In order to mount the additional power supplies in the existing rooms, the new power supplies should be compact by using the improved technology. Two types of DC power supplies, i.e. switch-mode (Chopper, PWM converter and zero voltage switching converters) and thyristor phase-controlled type (12 and 6 phases rectifiers), are applied in the BEPCII. The strategy for the BEPCII power supply system is to make the best use the existing devices, to apply the industry standard products and easy for operation and maintenance. The electro-magnetic interference problem will be carefully considered in the design especially for the switch-mode power supplies.

Vacuum System

The BEPCII poses two challenges to the vacuum system, one is the vacuum pressure, and the other is the impedance.

The dynamic vacuum at a high beam current should satisfy the requirements of the sufficient beam lifetime, and the low background in the IR. The design vacuum pressure of BEPCII is 8×10^{-9} Torr in the arc and 5×10^{-10} Torr in the IR. The distributed ion pumps are used inside the bending sections, while in the straight sections lumped ion pumps and NEG are applied.

To reduce impedance, the vacuum chamber should be as smooth as possible. Antechambers will be used for both electron and positron rings. Masks are placed upstream to such vacuum components as bellows in order to prevent them from exposure of synchrotron radiation.

IR and Superconducting Insertion Magnets

The design of IR has to accommodate competing and conflicting requirements from the accelerator and the detector. Many equipments including magnets, beam diagnostic instruments, masks, vacuum pumps, and experiment detector must coexist in a very small region. Figure 6 demonstrates a 3D sketch of the half IR.

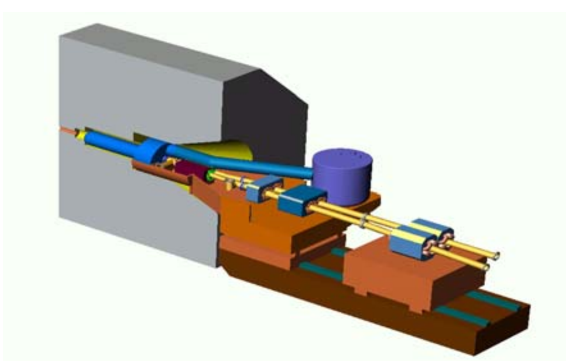

Figure 6: A 3D sketch of the IR.

The support, installation, background shielding, vacuum pumping and many other issues in the IR are carefully studied. A mock-up of IR installation is carried out to demonstrate the designed procedure.

A pair of quadrupoles will be inserted into the BESIII detector to squeeze the β function at IP. Two types of insertion quadrupoles were considered, one is permanent magnet and the other is superconducting magnet. The Permanent magnets are compact and no power supply is required. However, it is difficult to satisfy the wide operation range of the beam energy in the BEPCII using this type of magnets. Superconducting magnets can provide strong and adjustable magnetic field. A special pair of superconducting IR magnets are designed with main and skew quadrupole, compensation solenoid and dipole coils.

Instrumentation and Control

The instrumentation system provides precise and sufficient information about the beams. It consists of 132 beam position monitors (BPM's), 2 DCCT's, 2 bunch current monitors, 8 fluorescent screens monitors and 2 synchrotron radiation monitors in the BEPCII storage rings. Transverse and longitudinal feedback systems will be equipped in order to damp beam instabilities

The control system contains the computer control, the timing, the interlock and the communication subsystems. The storage rings and the injector should be operated in either the central control room or the local control room. The control system will be based on the EPICS environment to provide a friendly man-machine interface for operators.

BUDGET AND SCHEDULE

The budget of the BEPCII project is estimated as 640 million RMB. The project is scheduled to complete by the end of 2007.

SUMMARY

- The BEPC has been well operated with many exciting HEP and SR results for 15 years since it was put into operation in 1989.
- The BEPCII is designed with a double-ring structure and its design luminosity is two orders of magnitude higher than the present BEPC.
- Some key technologies are being developed in order to achieve the scientific goals of the BEPCII.

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